FARADAY, MICHAEL (*b.* Newington, Surrey [now part of Southwark, London], England, 22 September 1791; *d.* Hampton Court, Middlesex, England, 25 August 1867), *chemistry, physics.*

Early Life and Education. Michael Faraday was born into a poor family, of which he was the third of four children. His father, James, was a blacksmith who had left his own smithy in Outhgill, near Kirkby Stephen, early in 1791 to seek work in London. His increasing ill health prevented him from providing more than the bare necessities for his family. Faraday later recalled that he was once given a loaf of bread, which was to feed him for a week. James Faraday died in 1809. Michael's mother, the former Margaret Hastwell, was the mainstay of the family. She made do with what she had for material needs, but clearly offered her younger son that emotional security which gave him the strength in later life to reject all social and political distinctions as irrelevant to his own sense of dignity. She died in 1838.

There are no sources for Faraday's early years, so it is impossible to say what effects they had on him; we can only infer them from his adult life. His contemporaries uniformly described him as kind, gentle, proud, and simple in both manner and attitude. He loved children, although he had none of his own, and never lost his enthusiasm for natural beauty, especially such grandiose spectacles as a thunderstorm or an alpine waterfall. Such traits, when taken in conjunction with his solicitude for the success of his older brother, Robert, as a gas fitter and for the education of his younger sister, Margaret, bespeak a close-knit family, enjoying simple pleasures but raised in all propriety by stern but loving parents.

The one early influence of which there can be no doubt was that of religion. Faraday's parents were members of the Sandemanian Church, and Faraday was brought up within its discipline. The Sandemanian religion is a peculiar offshoot of Protestant Christianity. It is fundamentalist in the sense that Sandemanians believe in the literal truth of Scripture, but its emphasis is not on the fire and brimstone of most fundamentalist sects. Rather, it stresses that love and sense of community which marked the primitive Christian Church. It was this love and sense of community which were to sustain Faraday throughout his life. His friend and close associate at the Royal Institution, John Tyndall, a self-styled agnostic, wrote in some puzzlement in his journal for Sunday, 24 October 1852: "I think that a good deal of Faraday's week-day strength and persistency might be referred to his Sunday Exercises. He drinks from a fount on Sunday which refreshes his soul for a week" (Royal Institution, "Tyndall's Journals," MS, V, 163).

Faraday drew more than strength from his religion. It gave him both a sense of the necessary unity of the universe derived from the unity and benevolence of its Creator and a profound sense of the fallibility of man. Both are worth stressing. The origins of field theory are to be found in Faraday's detailed experimental researches on electricity, but the speculations and imaginings which led him to the experiments and the courage which permitted him to publish physical heresies owe something to his unquestioning belief in the unity and interconnections of all phenomena. This belief, in turn, derived from his faith in God as both creator and sustainer of the universe. The fallibility of man was clearly described in the Book of Job, and this was the book in Faraday's Bible which he had marked the most with marginal emphases. Faraday never engaged in scientific polemics. He presented his results to his peers, having done his best to assure that his experiments were accurate and his reasoning sound. If he were wrong, better experiments and sounder reasoning would prevail and his beloved science would progress. He considered himself to be merely an instrument by which truth was revealed. To insist upon his infallibility would border on blasphemy. He was content to publish his results and let posterity judge how close he had come to being right.

These qualities of Faraday became apparent only when he was in the full tide of fame. In his youth, it seemed unlikely that he would ever have the opportunity to exercise them, at least in the pursuit and presentation of scientific truths. His formal education was almost nil, consisting of the rudiments of reading, writing, and ciphering. When he was thirteen years old, Faraday helped contribute to the family earnings by delivering newspapers for a Mr. G. Riebau of 2 Blandford Street. Riebau was an émigré from France who had fled the political maelstrom of the French Revolution. He not only let out newspapers but also sold and bound books. When Faraday turned fourteen, he was apprenticed to Riebau to learn the art of bookbinding. It was in the seven years of his apprenticeship that Faraday developed the extraordinary manual dexterity that was to distinguish his later experimental researches. The proximity of books stocked for sale and brought in to be rebound stimulated his mind. He became an omnivorous reader, absorbing fact and fancy in equal amounts. The result was a severe case of intellectual indigestion as Faraday became the repository of hosts of unconnected statistics and ideas.

His condition was relieved by the discovery of an elementary treatise, *The Improvement of the Mind,* written by an eighteenth-century clergyman, Isaac Watts. This treatise, as Riebau reported, was "frequent took in his Pocket," and Faraday followed each

of Watts's suggestions for self-improvement. He began to keep a commonplace book, in which he could record ideas and interesting observations; he attended lectures and took notes; he began a correspondence with a young man, Benjamin Abbott, with the express hope of improving himself; he later helped found a discussion group devoted to the exchange of ideas. All these things Watts strongly recommended. But Watts went further than providing mechanical aids to learning; he also presented a philosophy which appeared to protect its adherents from false theories and intellectual delusions. Accurate observation of facts and precision in language would prevent a philosopher from premature generalization, which had led many an unwary student astray. This advice, together with his deep sense of human fallibility, reinforced the caution with which Faraday later approached natural philosophy. He never embarked upon an explanation without first testing for himself the facts that needed explanation. Mere reading of the results of others never satisfied him. Some of his most brilliant investigations owed their origin to a casual observation of an anomaly when Faraday checked his facts. And it was not until every fact had been checked and rechecked that Faraday would generalize. Watts had a very attentive pupil.

Faraday's passion for science was first aroused by a chance reading of the article "Electricity" in a copy of the *Encyclopaedia Britannica* which he was rebinding. His curiosity was piqued, and he set out to check what facts he could by means of a small electrostatic generator which he constructed out of some old bottles and waste lumber. The article had been written by one James Tytler, who espoused a somewhat idiosyncratic view of the nature of electricity. For Tytler, all electrical effects could be explained by assuming the existence of a peculiar fluid whose various modes of motion would account for optical and thermal, as well as electrical, phenomena. Electricity was likened by Tytler to a vibration, rather than a flow of material particles through space, and this view permitted him to suggest answers to such thorny questions as why conductors conduct electricity and insulators do not. In the course of his article, Tytler also took the opportunity to demolish the two-fluid theory of electricity then current on the Continent and the Franklinian one-fluid theory popular in Great Britain.

One should be wary of drawing too far-reaching consequences from any single influence, but there are a number of aspects of Tytler's article and its possible effects on Faraday that deserve mention. Tytler was, first of all, a scientific heretic presenting a view that had few supporters. As such, he was both belligerent and challenging, and undoubtedly stirred Faraday to exercise his own judgment more than if the subject had been presented calmly, without controversy, as Truth. Tytler's defensive posture also forced him to attack the more orthodox theories and underline their very real weaknesses. If nothing else, these criticisms must have made Faraday skeptical of the accepted theories and forced him to keep an open mind on controversial points. When he later challenged both the one-fluid and the two-fluid theories, he was able to do so in precisely those areas where Tytler had first sown doubts. His challenge to orthodox electrical theories in 1838 was couched in Tytlerian terms. Current electricity, for Faraday as for Tytler, was a vibration, not a material flow. How much Faraday owed to Tytler is impossible to assess, but the influence was strong enough to lead Faraday to refer to Tytler's article a number of times in the laboratory diary that he kept from 1820 on.

With the reading of Tytler's article, Faraday began the pursuit of science in earnest. In the London of the early nineteenth century, however, it was difficult for an apprentice bookbinder to find many sources of scientific enlightenment. He could and did attend public lectures, but there were no night schools, no correspondence courses, no public libraries from which he could gain scientific enlightenment. He was, therefore, doubly fortunate to fall in with a group of young men with a common passion for science. They had come together as the City Philosophical Society in 1808 and were led by John Tatum, at whose house they met every Wednesday night. Tatum would deliver a lecture on a scientific subject and then throw open his library to the members of the society.

Faraday was introduced into this company in February 1810, when he attended his first lecture. At the City Philosophical Society, he received a basic education in the sciences, attending and taking careful notes on lectures on electricity, galvanism, hydrostatics, optics, geology, theoretical mechanics, experimental mechanics, chemistry, aerology (pneumatic chemistry), astronomy, and meteorology. These lectures should not be overestimated, for they were often mere catalogs of facts (mineralogy is an example) but, when possible, Tatum illustrated them with experiments and introduced his avid listeners to interesting pieces of scientific apparatus. It was at the City Philosophical Society, for example, that Faraday first saw a voltaic pile in operation.

Faraday's interest was increasingly focused on science. It was this interest that led him to the discovery of a work which he lauded throughout his life, Jane Marcet's *Conversations on Chemistry.* Mrs. Marcet's treatment of chemistry differed considerably from other contemporary, more technical accounts. She

had written it for those people, like herself, who had been entranced by the lectures of Humphry Davy at the Royal Institution of Great Britain. Davy approached chemistry as if it were the key to the ultimate mysteries of nature, and Mrs. Marcet did likewise. Here was no dry catalog of chemical facts, or recipes, but a grand scheme which tied together chemical reactions, electrical relations, and thermal and optical phenomena. The impact on Faraday was considerable. The simplicity of his views on electricity was forever destroyed, his thoughts were directed specifically to chemistry, and, most important of all, he was introduced to the thoughts of Humphry Davy, who became, for him, the example of what he would like to be.

Faraday and Humphry Davy. There was, seemingly, little chance that Michael Faraday, bookbinder's apprentice, would ever become anything other than Michael Faraday, bookbinder. But one of Riebau's customers offered him tickets to Davy's lectures at the Royal Institution. He went, took careful notes, and copied them out in a clear hand. Each scientific point made by Davy was grasped eagerly and recounted to his friends at the City Philosophical Society. But this was mere playing at science, and it was with a heavy heart that Faraday, in October 1812, accepted the end of his apprenticeship and prepared to devote himself to bookbinding instead of his beloved chemistry. An accident changed his life and the life of science. In late October, while examining chloride of nitrogen, a very unstable substance, Davy was temporarily blinded by an explosion. Faraday was recommended to Davy as an amanuensis, and Davy was pleased to have him. In December, Faraday sent Davy the carefully bound notes he had taken at Davy's lectures. Davy was flattered but could do nothing at that time to help his young admirer. In February 1813, however, an assistant in the laboratory of the Royal Institution was fired for brawling. Davy immediately sent for Faraday and on 1 March 1813, Faraday took up his new position at the Royal Institution.

Davy exerted the most important influence on Faraday's intellectual development. Davy's mind was both penetrating and wide-ranging. He seems to have been an omnivorous reader interested in metaphysics as well as chemistry, poetry as well as physics. His science was characterized by brilliant flashes of insight soundly supported by experimental evidence. Although he never committed himself to a specific theoretical or metaphysical viewpoint, he was aware of and often used those that offered clues to the nature of matter and its forces. In the early nineteenth century, there were a number of points of view which could provide the chemist with guidelines worth following. There was, first of all, an English tradition in chemistry which could be traced back to the patron saint of English science, Sir Isaac Newton. It took Newton's work on force and raised it to the level of a universal science. The classic example in the eighteenth century is Gowin Knight's *An Attempt to Demonstrate That All the Phenomena in Nature May Be Explained by Two Simple Active Principles, Attraction and Repulsion* (1748), whose message can be seen from the title. There seems little reason to doubt that both Faraday and Davy had read Knight's work. It was a part of the English scientific tradition and, more important, was easily available in the library of the Royal Institution.

But Knight's work was relatively crude. Although he reduced matter to the forces of attraction and repulsion, he separated the two, hypothesizing one kind of matter with attractive force only and another consisting solely of repulsive force. The association of these two forms of matter gave rise to the phenomena of the sensible world. A more subtle solution to the problem of complexity and of the nature of matter was provided by the Jesuit Rudjer Bošković in his *Philosophiae naturalis theoria redacta ad unicam legem virium in natura existentium,* which first appeared in 1758. Like Knight, Bošković dismissed the reality of matter and substituted forces but, unlike Knight, was able to combine the forces of attraction and repulsion in one "atom." In Figure 1, the pattern of forces of a Boscovichean atom is represented graphically. The point at *O* is a mathematical point which serves merely as the center of the forces of which the atom consists. Beyond *H*, the atomic force is attractive, decreasing inversely as the square of the distance, thus satisfying the Newtonian principle of universal attraction. From *H* to *A,* the force varies, according to the distance from *O,* in a continuous fashion from attractive to repulsive and back to attractive. The number of such variations can be multiplied at will to account for phenomena. From *A* to *O,* the force becomes increasingly repulsive, reaching infinite repulsion at *O* and thereby preserving impenetrability as a characteristic of "matter." These point-atoms were likened by Bošković to the points that make up the lines of the letters of the alphabet. A combination of the point-atoms gave the chemical elements, just as a combination of points made up the letters. Combinations of elements yielded the chemical compounds, and so on. Ultimately, then, all "matter" is one; observable complexities were the result of successive levels of complexity of particulate arrangements.

This system was particularly appealing to chemists

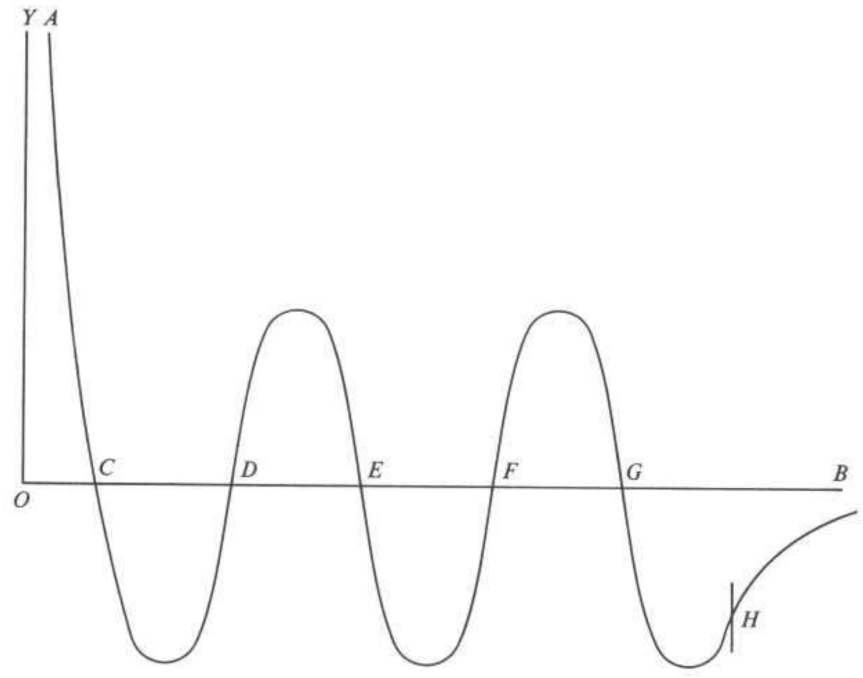

FIGURE 1

of philosophical disposition. It reconciled simplicity and complexity, providing a fundamental order in place of the taxonomic confusion engendered by the myriad chemical compounds and the ever-growing number of chemical elements. It also offered some insight into such specifically chemical problems as elective affinity by referring to the patterns of forces which could interact to create stable compounds. Davy remarked in his last years that he had found Bošković's theory of some importance in the development of his ideas and, in 1844, Faraday publicly declared his preference for Boscovichean atoms over those suggested by Dalton. Just how important Bošković's theory was for Faraday is currently a matter of scholarly dispute. I shall here insist that it was fundamental, but the reader is warned that my discussion of Faraday's use of it is controversial.

Knight and Bošković provided the justification for the unity of matter in which both Faraday and Davy believed. They did not, however, provide the concept of the unity of force. Both Knight and Bošković, after having composed their primary matter(s) from attractive and repulsive forces, gave material explanations for such phenomena as light and electricity. It may, of course, be argued that since all phenomena are ultimately the results of attractive and repulsive forces, then all phenomena are convertible into one another. But no such argument was ever made, to my knowledge, by those within the English tradition or by those who were partial to Bošković. Yet Faraday wrote in 1845: "I have long believed in the unity of force," and his work from 1831 on was devoted to the conversion of one force into another. Whence came this conviction of the unity and convertibility of forces? Again, what follows is controversial, but it seems to make sense of what otherwise appears inexplicable and is, therefore, worth putting forward, albeit with considerable caution.

The doctrine of the unity and convertibility of forces is the product of German philosophy at the end of the eighteenth century. It was first suggested by Immanuel Kant in his *Metaphysische Anfangsgründe der Naturwissenschaft* (1786) and then developed by F. J. Schelling in his *Naturphilosophie.* The disciples of Schelling—the *Naturphilosophen,* among whom may be counted Hans Christian Oersted, the discoverer of the first force conversion (electromagnetism)—used this idea as the basic guiding thread in their researches. What is extremely difficult is to connect this movement in Germany and Scandinavia to Davy and Faraday. The one possible link, since neither Davy nor Faraday read German and translations were unavailable, is the poet and metaphysician Samuel Taylor Coleridge. He visited Germany in 1798–1799 and came back to England with his head overflowing with *Naturphilosophie.* He and Davy were close friends in the early 1800's and it seems likely, indeed inevitable, given Coleridge's enthusiasm and love of conversation, that he and Davy discussed *Naturphilosophie* in some detail. The unity and convertibility of forces was the kind of idea Davy always liked to keep in the back of his mind without com-

mitting himself to it. It might suggest some experiments and was, therefore, a potentially useful way of looking at the world. If he passed it on to Faraday, it fell on eager ears, for there can be no doubt of Faraday's commitment to it. The difference in their reaction may have lain in their different attitudes toward religion rather than toward science. Both men were religious, but Faraday was by far the more intense in his religious feelings and more determined in his devotion. One of the reasons Coleridge had been so enthusiastic in his acceptance of *Naturphilosophie* was that it appeared to contradict materialism and offer a place to spirit in the world. Faraday may have felt the same. Certainly the unity and convertibility of force offered a more appealing view of God's creation than the chaotic interplay of material atoms in which most scientists believed.

If we accept this admittedly hypothetical reconstruction, we can suggest the course of Faraday's development under Davy's tutelage. The unity and convertibility of force would first appeal to the apprentice chemist, for it bound the universe together in an aesthetically and theologically satisfying way. From here, it was a short step to the acceptance of, or at least the willingness to think in terms of, Boscovichean atoms. The English tradition of dynamic atomism made such a step intellectually respectable, for this tradition had based its insistence on the ultimate reality of force on sound empirical arguments which Faraday was to repeat in 1844 and 1846. It is within this intellectual and philosophic framework that his work should be viewed.

There was ample opportunity for Davy and Faraday to discuss these fundamental aspects of the nature and structure of physical reality. Soon after Faraday's employment at the Royal Institution, Davy decided to visit the Continent, and he asked Faraday to accompany him and Lady Davy. The party set out on 13 October 1813 and during 1813 and 1814 visited France and Italy, where Faraday met many of the leading scientists of the day. During this tour, Davy discoursed on every scientific subject under the sun, and Faraday eagerly drank it all in. Faraday became fully conscious, during this period, of the philosophical complexities underlying the apparent simplicity of chemical science and even more aware of the dangers of both methodological and metaphysical complacency.

Journeyman Chemist. Upon his return to London in April 1815, Faraday threw himself into chemistry with the enthusiasm that marked his whole scientific life. He assiduously searched all the scientific journals available to him, keeping a detailed bibliographical record of everything he read and carefully noting everything of interest to him. In 1816 he published his first paper, "Analysis of Caustic Lime of Tuscany," which was followed by a series of short (and inconsequential) articles on subjects suggested to him by the researches of Davy and William T. Brande, Davy's successor as professor of chemistry at the Royal Institution. By 1820 Faraday had established a modest but solid reputation as an analytical chemist, so much so that he was involved in court cases requiring expert testimony. One such case involved the question of the ignition point of heated oil vapor. This, together with his brother's involvement in the new gas lighting of London, led Faraday to investigate the general properties of the various oils used for heating and lighting. From these researches came the discovery of benzene in 1825.

But Faraday's mind ranged far wider than the composition of lime or illuminating gas. One of his earliest chemical enthusiasms had been Davy's work on chlorine, in which Davy had exploded Lavoisier's theory of acids by showing that not all acids contain oxygen, as the name of that element implied. Hydrochloric acid consisted solely of hydrogen and chlorine. Davy's demonstration that chlorine supported combustion also destroyed the unique place among the elements allotted to oxygen as the sole supporter of combustion, and thereby tended to weaken Lavoisier's magistral chemical synthesis. But this demonstration raised an important problem, and it was to this problem that Faraday turned. If chlorine were a supporter of combustion, as the almost explosive nature of the combination of iron with chlorine clearly demonstrated, then why did chlorine not combine with carbon, the combustible substance par excellence? All attempts at "burning" carbon in chlorine were unsuccessful, but Faraday was convinced that compounds of chlorine and carbon must exist. In 1820 he produced the first known compounds of chlorine and carbon, C_2Cl_6 and C_2Cl_4. These compounds had been produced by the substitution of chlorine for hydrogen in "olefiant gas," our modern ethylene. This was the first substitution reaction; such reactions, in the hands of Charles Gerhardt and Augustin Laurent in the 1840's, were to be used as a serious challenge to the dualistic electrochemical theories of J. J. Berzelius.

Beyond his work in analytical and pure chemistry, Faraday showed himself to be a pioneer in the application of chemistry to problems of technology. In 1818, together with James Stodart, a cutler, he began a series of experiments on the alloys of steel. Although he was able to produce alloys of superior quality, they were not capable of commercial production because they required the use of such rare metals as platinum,

rhodium, and silver. Nevertheless, Faraday demonstrated that the increasingly urgent problem of producing higher-grade steels could be attacked by science. The later work on steel of Henry Sorby, Henry Bessemer, and Robert A. Hadfield was based directly on Faraday's work in the early part of the century.

In 1824 Faraday was asked by the Royal Society to conduct experiments on optical glass. Again his researches were inconclusive, but he paved the way for later improvements in glass manufacture. It was in these experiments that he produced a glass containing borosilicate of lead and with a very high refractive index. This was the glass he used in 1845 when he discovered the rotation of the plane of polarization of a light ray in an intense magnetic field.

The 1820's were busy years for Faraday beyond his chemical researches. In 1821 he married Sarah Barnard, the sister of one of the friends he had made at the City Philosophical Society. Their marriage was an extremely happy one and sustained Faraday throughout the extraordinary mental exertions of the next forty years. Sarah Barnard was not an intellectual. Once, when she was asked why she did not study chemistry, she replied, "Already it is so absorbing, and exciting to him that it often deprives him of his sleep and I am quite content to be the pillow of his mind." Faraday needed no one to whom to talk about his research. His dialogue was with nature. "I do not think I could work in company, or think aloud, or explain my thoughts . . .," he remarked near the end of his life. He founded no school and left no disciple who had been formed in his laboratory.

In the 1820's the precarious financial position of the Royal Institution also demanded Faraday's attention. He helped support the institution by performing chemical analyses, and he contributed to its fiscal stability by instituting the Friday evening discourses in 1825. He gave more than a hundred of these lectures before his retirement in 1862. They served to educate the English upper class in science, and part of the growing support for science in Victorian England may legitimately be attributed to the efforts of Faraday and his fellow lecturers to popularize science among those with influence in government and the educational establishment.

Early Researches on Electricity. During these busy years, Faraday was forced to push his love for electricity into the background. Yet it was never far from his thoughts, as the events of 1821 and 1831 reveal. In 1821 a series of brilliant researches culminated in the discovery of electromagnetic rotation; in 1831, seemingly out of nowhere, came the discovery of electromagnetic induction and the beginning of the experimental researches in electricity which were to lead Faraday to the discovery of the laws of electrochemistry, specific inductive capacity, the Faraday effect, and the foundations of classical field theory. These researches, in both 1821 and 1831, are all of a piece; and it would be well here to make explicit what I think is the theoretical thread that holds them together.

By 1821 we know that Faraday was aware of and even toying with the concept of Boscovichean point-atoms. This is not to say that Faraday was a disciple of Bošković, for he certainly did not follow the Boscovichean system in his work. But the notion of atoms as centers of force had a strong appeal for him, and it is this notion that, I should like to suggest, provided the conceptual framework for his work on electricity. In particular, there were two specific consequences of the theory of point-atoms which were to be fundamental to Faraday's discoveries. The first was the emphasis upon complex patterns of force that followed logically from the consideration of the interaction of numbers of Boscovichean particles. It should be remembered that Boscovichean atoms were not the atoms of early nineteenth-century chemistry. Rather, the chemical elements were agglomerates of Boscovichean atoms whose specific chemical properties were the direct result of the patterns of force produced by the intimate association of point-atoms. When Faraday thought of material particles, therefore, he did not envision them as submicroscopic billiard balls with which certain rather simple forces were associated, but rather as centers of a complex web of forces.

Put another way, the orthodox scientist of the 1820's tended to think in terms of central forces emanating from particles, and central forces always act in straight lines between particles. Faraday's vision was far more intricate, and it permitted him to contemplate forces in manifold ways. An example may be useful here. Oersted's discovery of a circular magnetic "force" around a current-carrying wire was explained by André-Marie Ampère as the resultant of central forces emanating from current elements in the wire. To Faraday, the circular "force" was simple and could be used to explain the apparent polarity (or central forces) of magnetic poles. No one but Faraday could or did take a circular "force" seriously, but this was the germ of the idea of the line of force which was to be central to the development of Faraday's theories.

The second consequence involved a subtle shift in point of view away from the orthodox physics of the day. Boscovichean atoms, as force, were infinite in extent because the forces associated with atoms extended to infinity. Thus all material associations on

the molecular level were really interpenetrations of fields of force, if I may be excused the anachronism. All particles, then, were associated with one another; the only differences were in the degrees of approximation of molecular or atomic centers of force. A displacement of a particle, anywhere in the universe, ought to affect every other particle. The same conclusion, of course, may be drawn from orthodox action-at-a-distance physics, but it is neither obvious nor obtrusive. In the theory of point-atoms it is both.

Furthermore, it suggests a mode of action which Faraday seized upon in his researches on the nature of electricity. Orthodox theory assumed the existence of one or two "imponderable" electrical fluids with whose particles specific electrical forces were associated. Electrical energy was transferred from place to place by the translation of these particles. The interlocking of force particles permitted energy to be transferred without the permanent displacement of the particles by means of the vibration of the particles. If a line of particles could be put under a strain, this line could then transmit energy either by the rapid breakdown and buildup of the strain or by vibrating transversally to the direction along which the strain was exerted. The first kind of "vibration" was that suggested by Faraday in 1838 to explain spark discharge, electrochemical decomposition, and ordinary electrical conduction. The second sort of vibration was tentatively put forward by Faraday in 1846 in his "Thoughts on Ray Vibrations" to account for the transmission of light through a vacuum without having recourse to a vibrating medium such as the luminiferous ether.

All this was far in the future in 1821, when Faraday was persuaded to take up the subject of electromagnetism by his friend Richard Phillips, an editor of *Philosophical Magazine.* Ever since Hans Christian Oersted's announcement of the discovery of electromagnetism in the summer of 1820, editors of scientific journals had been inundated with articles on the phenomenon. Theories to explain it had multiplied, and the net effect was confusion. Were all the effects reported real? Did the theories fit the facts? It was to answer these questions that Phillips turned to Faraday and asked him to review the experiments and theories of the past months and separate truth from fiction, groundless speculation from legitimate hypothesis. Faraday agreed to undertake a short historical survey but he did so reluctantly, since his attention was focused on problems of chemistry rather remote from electromagnetism.

His enthusiasm was aroused in September 1821, when he turned to the investigation of the peculiar nature of the magnetic force created by an electrical current. Oersted had spoken of the "electrical conflict" surrounding the wire and had noted that "this conflict performs circles," but this imprecise description had had little impact upon Faraday. Yet as he experimented he saw precisely what was happening. Using a small magnetic needle to map the pattern of magnetic force, he noted that one of the poles of the needle turned in a circle as it was carried around the wire. He immediately realized that a single magnetic pole would rotate unceasingly around a current-carrying wire so long as the current flowed. He then set about devising an instrument to illustrate this effect. (See Figure 2.) His paper "On Some New Electro-Magnetical Motions, and on the Theory of Magnetism" appeared in the 21 October 1821 issue of the *Quarterly Journal of Science.* It records the first conversion of electrical into mechanical energy. It also contained the first notion of the line of force. Faraday, it must be remembered, was a mathematical illiterate. His experiments revealed a circular "line" of magnetic force around a current-carrying wire and he found no difficulty in accepting this as a simple fact. To his mathematically trained contemporaries, such a force could not be simple but must be resolved into central forces. This is what Ampère had done so ingeniously in his early papers on electromagnetism. Ampère's sophisticated mathematical reasoning could have no

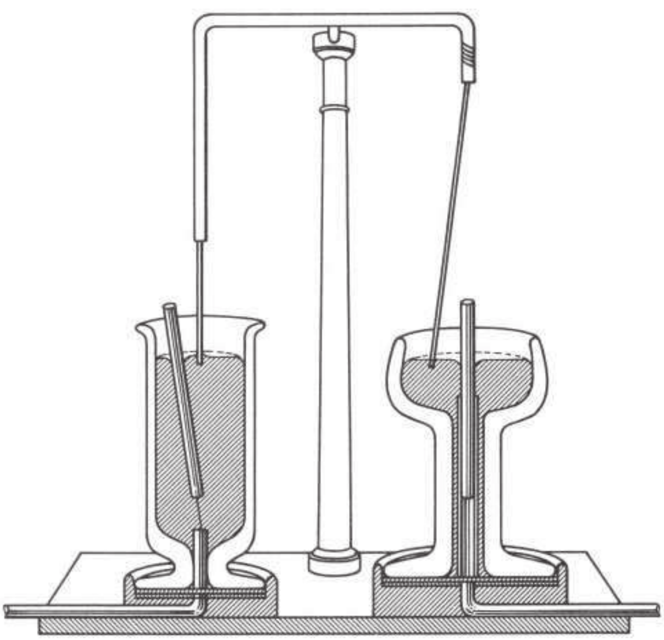

FIGURE 2. Faraday's apparatus for illustrating electromagnetic rotation. At left, a cylindrical bar magnet, plunged into a beaker of mercury (which was part of the electrical circuit), rotated around the end of a current-carrying wire that made contact with the mercury. At right, the magnet was fixed and the wire was so mounted that it could turn about the point of suspension, and thus rotate around the magnetic pole.

effect on Faraday and he refused to move from what he considered the bedrock of experiment. Stubbornness, however, is no virtue in science and he was forced to face the problem of deriving central forces from his circular force in order to explain the "simple" attractions and repulsions of magnetic poles. His solution was both simple and elegant. If a straight current-carrying wire were bent into a loop, then the circular lines of magnetic force would be arranged in such a way as to concentrate them within the loop and the magnetic "polarity" of the loop would reflect this concentration. That there were no "poles" or termini of the magnetic force, Faraday showed by another simple demonstration. He wound a glass tube with insulated wire and then placed it half-submerged in water. A long magnetic needle was affixed to a cork so that it could float freely on the water. When a current was passed through the wire surrounding the glass tube, "poles" were formed at opposite ends of the tube and the north pole of the needle was attracted to the south pole of the helix. If an ordinary magnet had been used, the needle would have approached the electromagnet and clung to it, giving the illusion that the south pole attracted the north pole.

But in Faraday's setup the result was surprising. The needle moved toward the helix, entered the glass tube and continued through it until the north pole of the needle was situated at the north pole of the helix. The result was as Faraday had expected; it was merely another example of his electromagnetic rotations. A single magnetic "pole" would continue to move around and through the helix and never come to rest. The line of force along which it moved was the resultant of the circular magnetic forces surrounding the wires of the helix and did not emanate in straight lines from the "poles" of the magnet.

Thus Faraday's work on electromagnetic rotations led him to take a view of electromagnetism different from that of most of his contemporaries. Where they focused on the electrical fluids and the peculiar forces engendered by their motion (Ampère's position), he was forced to consider the line of force. He did not know what it was in 1821, but he suspected that it was a state of strain in the molecules of the current-carrying wire and the surrounding medium produced by the passage of an electrical "current" (whatever that was) through the wire. Such a state of strain, he knew, was transmitted some distance from the source of the strain, the current-carrying wire. Might it not be legitimate to speculate that if the strain could be intensified and concentrated, it might induce a similar state in a neighboring wire?

In the years between 1821 and 1831, Faraday returned sporadically to this question. He attempted to detect the strain by passing plane polarized light through an electrolyte through which a current was passing; he queried the best form of magnet to produce the maximum strain, concluding that it might be "a very thick ring"; he attempted to induce an electrical current by means of static electricity; but all to no avail. Yet in these years his ideas gradually developed and clarified. The wave theory of light revealed how strains could transmit energy; the work of his friend Charles Wheatstone on sound, particularly on Chladni figures, which Faraday illustrated to audiences at the Royal Institution, showed how vibrations could produce symmetrical arrangements of particles; the discovery of "magnetism by rotation" by François Arago in 1825 (Arago's wheel) revealed to him the insufficiency of Ampère's electrodynamic theory.

In 1831 Faraday learned of Joseph Henry's experiments in Albany, New York, with powerful electromagnets in which the polarity could be reversed almost instantaneously by a simple reversal of "current" direction. The stage was set. An electromagnet, in the shape of a thick iron ring, wound on one side with insulated wire should set up the powerful strain; the strain should be conducted through the particles of the ring, which would then be thrown into a peculiar arrangement, much as the particles of dust were affected on a neighboring iron plate when one close by was set into vibration by a violin bow; the resultant arrangement would distort the intermolecular forces by which the iron molecules of the ring cohered, and this strain should then be detected by a secondary winding on the other side of the iron ring. On 29 August 1831, Faraday tried the experiment. When the primary circuit was closed, the galvanometer in the secondary circuit moved. An electrical "current" had been induced by another "current" through the medium of an iron ring. This discovery is always called the discovery of electromagnetic induction, but it should be noted that it is no such thing.

It was not until some weeks later that Faraday discovered the conditions under which a permanent magnet could generate a current of electricity (17 October 1831). It was at this date that he could declare that he had demonstrated the reverse of Oersted's effect, namely, the conversion of magnetic force into electrical force. Further investigation led him to the invention of the first dynamo, whereby the reverse of his 1821 discovery of electromagnetic rotations could be accomplished. Mechanical force could be converted into electrical force by a simple machine. A copper disk, rotated between the poles of a magnet, produced a steady electrical current in a circuit run-

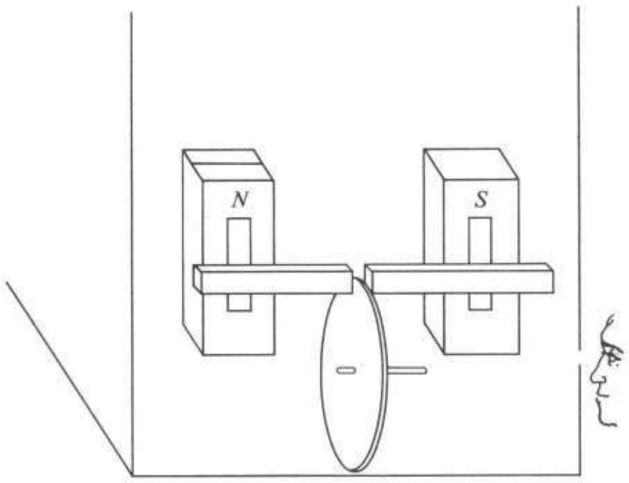

FIGURE 3

ning from the center of the disk through a wire to the edge of the disk. (See Figure 3.)

The concept of the line of force now moved to the very center of Faraday's thought, where it was to remain for the rest of his life. It was the line of force which tied all his researches on electricity and magnetism together. It was therefore with some embarrassment that he confessed, in his second series of *Experimental Researches in Electricity,* that he did not know what the line of force was. In the first series, he had described it as a strain imposed upon the molecules of the conducting wire and the surrounding medium by the passage of the electric "current." This state of strain he christened "the electrotonic state," but it defied every attempt at detection. His abandonment of the electrotonic state in the second series was only temporary, for without it Faraday was deprived of his basic concept. The electrotonic state had to exist, for there could be no doubt of the reality of the line of force. It was his attempts to relate the two which led him onward through the brilliant series of researches which culminated in his general theory of electricity in 1838.

Electrochemistry. The first and second series of *Experimental Researches* had been concerned with the relations between electricity and magnetism. In the summer of 1832 Faraday appeared to go off on a tangent, with an investigation into the identity of the electricities produced by the various means then known. His commitment to the unity of force led him to believe that the electricities produced by electrostatic generators, voltaic cells, thermocouples, dynamos, and electric fishes were identical, but belief was no substitute for proof. Furthermore, this identity had been challenged by Sir Humphry Davy's brother John, who insisted that electrical effects were not produced by a single agent but were the complex results of a combination of powers. There was little sense in continuing to work on electricity until this question was settled. It seemed like a routine investigation involving mere manipulative skill to demonstrate that electricity, no matter how produced, had the same effects. But in the course of this investigation Faraday was to be led to the laws of electrolysis and, more important, to challenge the concept of action at a distance.

Faraday's attack was straightforward. Searching the literature, he found reports of the similar effects of the various forms of electricity. The only real difficulties arose with static electricity. There were published reports that electrostatic discharges had both magnetic and electrochemical effects but, upon repeating the experiments, Faraday found them equivocal. Electrostatic discharge, for example, could magnetize needles, but Faraday found it impossible to produce a magnet in an electrostatic field. Similarly, William Hyde Wollaston had reported the decomposition of water by an underwater spark in 1801, but it was possible to view this decomposition as the result of the mechanical shock, the heat generated by the discharge, or both. To remove all possible doubts, Faraday turned his experimental skill to the examination of these two effects.

The magnetic effect of an electrostatic discharge was examined by means of a simple galvanometer. The discharge was "slowed down" by passing it through wet string. The galvanometer was deflected, thus settling the question once and for all. Here Faraday might have stopped, but he saw the opportunity to compare static and voltaic electricity quantitatively and was quick to seize it. An electrometer gave him a relative reading of static charge; the deflection of the galvanometer permitted him to correlate the charge with the discharge. Fortunately (and unbeknown to Faraday), his galvanometer here acted like a ballistic galvanometer, and he was able to conclude that "if the same absolute quantity of electricity pass through the galvanometer, whatever may be its intensity, the deflecting force upon the magnetic needle is the same." Faraday immediately proceeded to devise an apparatus by which he could compare, quantitatively, the currents produced by electrostatic and voltaic discharge. Insofar as electricity affected a galvanometer needle, then, Faraday had given conclusive proof of the identity of static and voltaic electricity. He had, furthermore, devised an instrument for the measurement of relative quantities of electricity.

The remaining problem was that of electrochemical decomposition by electrostatic discharge. Once again, the desired effect was produced without the ambiguity

of Wollaston's experiment. Faraday might have rested here, since the identity of electricities was what he had set out to prove, but the opportunity for further discoveries was clear and he set out to exploit it. The course was obvious. Both electrostatic and current electricity decomposed water; the "throw" of the galvanometer permitted the accurate measure of electrical quantity. Could not the quantity of electricity be correlated with the products of electrochemical decomposition? In answering this question, Faraday enunciated his two laws of electrochemistry: (1) Chemical action or decomposing power is exactly proportional to the quantity of electricity which passes in solution; (2) The amounts of different substances deposited or dissolved by the same quantity of electricity are proportional to their chemical equivalent weights. Thus, Faraday had not only proved the identity of electricities; he had added another link in the chain of the convertibility of forces. Electricity was not only involved in chemical affinity, as the invention of the voltaic cell had shown, but it was the force of chemical affinity. In 1881 Hermann von Helmholtz was to use Faraday's 1834 papers on electrochemistry as the experimental basis for his suggestion that electricity must be particulate, or Faraday's laws of electrochemistry would make no sense.

In the course of his electrochemical researches, Faraday made a discovery with revolutionary implications. As he varied the conditions under which electrostatic discharge produced electrochemical decomposition, he found to his surprise that no "poles" were required. Ever since the invention of the voltaic cell, electrochemists had assumed that the + and − terminals of the circuit acted as centers of force, which force, acting at a distance upon the molecules in solution, literally tore them apart. Hence the term "poles." But when Faraday passed an electrostatic discharge through some blotting paper soaked with a solution of potassium iodide into the air, the potassium iodide decomposed. Where, now, were the centers of force of orthodox theory? More important, what was "acting at a distance" upon the potassium iodide molecules? The mere passage of the "current" was sufficient to decompose the potassium iodide. The experiment with electrostatic discharge suggested to Faraday that decomposition was not effected by action at a distance.

In a series of ingenious experiments, Faraday went on to show that the molecules were not "torn apart" at all. Instead, the two components of a binary salt seemed to migrate in opposite directions through the solution, without ever becoming free chemical agents, until they reached the terminals upon which they were deposited. Faraday accounted for this strange behavior by claiming that the electric "current" exalted the affinities of the components of a salt on opposite sides of the compound molecules, thus permitting each component to leave its original partner and join with another close by. The electrical force determined the direction of this recombination, one component moving toward the "positive" terminal, the other toward the "negative." The "exaltation" was passed along from one molecule to the next, beginning from the terminals and moving out into the solution. There was no action at a distance, but only intermolecular forces created by the strain imposed by the electrical force. It is difficult to visualize this process without having recourse to point-atoms and the patterns of force which produced their chemical identity.

Such patterns of force could be distorted by the imposition of other forces, and this appears to be what Faraday meant by his use of the term "exaltation." Under the strain of electrical force, the affinities of the molecular components were both "exalted" and aligned, permitting their transfer through the solution. As in an American square dance "grand right and left," where each partner passes around the square by taking the hands of people passing in the opposite direction, the chemical elements in solution passed through the solution, ever bound to a partner, until they were freed at the termini. The process involved three steps: the creation of the initial strain by the imposition of the electrical force; the exaltation of the affinities along the direction of the electrical force, which exaltation caused the component atoms of the decomposing substances to shift in opposite directions and to be bound by partners moving the other way; and the "shift" in which the strain was momentarily relieved, only to be reimposed immediately by the constant application of the electric force at the termini. The electric force was transmitted by this rapid series of buildups and breakdowns of strain, and electrical energy could be transmitted in this fashion without the transfer of a material agent. It was even possible to deduce the second law of electrochemistry from this scheme. Each shift required the breaking of a chemical bond of specific strength, so it was to be expected that the total force employed (quantity of electricity) should bear some specific and simple relation to the total quantity of matter decomposed by this force.

In his published accounts, Faraday only hinted at what has been presented here as his theory of electrochemical decomposition. The conceptual framework was too conjectural for Faraday to present it to his co-workers in electrochemistry. But what he could and

did do was to publish his factual results and also prepare the way for a successful challenge to the prevalent theory by introducing a new nomenclature which was theoretically neutral. Instead of poles, which implied centers of force, Faraday used the term "electrode," which had no such implication. Similarly "cathode," "anode," "electrolysis," "electrolyte," "anion," and "cation" were merely descriptive terms. William Whewell of Trinity College, Cambridge, was the source of most of these neologisms.

Faraday's Theory of Electricity. Faraday's electrochemical researches suggested to him a new perspective on electrostatics. If electrochemical forces did not act at a distance, was it preposterous to think that electrostatic forces also were intermolecular? The researches of Charles Coulomb in the 1780's had appeared to settle that question once and for all in favor of action at a distance, but Faraday drew courage from his electrochemical work and sought to find experimental confirmation for his new point of view. Two consequences flowed logically from the substitution of intermolecular forces for action at a distance. First, the electrostatic force ought to vary if it depended upon the ability of the molecules of a medium to transmit it and, second, this force ought to be transmitted in curved lines, since the transmitting molecules occupied a volume of space, rather than in the straight lines assumed by action-at-a-distance physics. Experimental confirmation of both these conclusions was quick in coming. The inductive force did vary when different substances were used to transmit it. The discovery of specific inductive capacity was an important structural element in the construction of Faraday's novel electrical theory. The inductive force was also shown to be transmitted in curved, not straight, lines, thus confirming once again Faraday's belief in intermolecular forces.

By 1838 Faraday was in a position to put all the pieces together into a coherent theory of electricity. The particles of matter were composed of forces arranged in complex patterns which gave them their individuality. These patterns could be distorted by placing the particles under strain. Electrical force set up such a strain. In electrostatics, the strain was imposed on molecules capable of sustaining large forces; when the line of particulate strain gave way, it did so with the snap of the electric spark. Lightning was the result of the same process on a larger scale. In electrochemistry, the force of the "breaking" strain was that of the chemical affinities of the elements of the chemical compound undergoing electrochemical decomposition. The shift of the particles of the elements toward the two electrodes momentarily relaxed the strain, but it was immediately re-created by the constant application of electric force at the electrodes upon the nearest particles of the electrolyte. This buildup and breakdown of interparticulate strain, passing through the electrolyte, constituted the electrical "current." It was a transfer of energy which did not entail a transfer of matter; Faraday's caution in adopting the term "current" appeared justified. The same situation obtained in ordinary conduction through a wire. The molecules of good conductors could not sustain much of a strain at all, so here the buildup and breakdown of the strain was exceptionally rapid and the "conduction" was therefore correspondingly good.

The theory was elegant, firmly based on experiment, and complete. It was also heretical, challenging almost all the fundamental concepts of orthodox electrical science. Faraday knew this and put it forward with appropriate caution. The experimental results were clearly and firmly reported; the theoretical aspect was hedged with fuzzy and tentative language, hesitantly and sometimes confusedly presented. It is, I think, fair to say that no one in the 1830's took the theory seriously. Even Faraday was unable to advocate it with the necessary vigor. The strain of eight years of unremitting intellectual effort at the farthest frontier of electrical theory ultimately broke his powerful mind. In 1839 he suffered a nervous breakdown, from which he never really recovered. For five years he was unable to concentrate his mental faculties on the problems of electricity and magnetism. He passed this time by devoting himself to the affairs of the Royal Institution and such other researches as did not require his total intellectual commitment. It was in these years, for example, that he extended his earlier work on the condensation of gases. He was able here to use his experimental talents to the full without being forced to focus his mind on the consequences.

Even during these years, Faraday kept returning to his electrical theory. In 1844 he published a small paper entitled "Speculation Touching Electrical Conduction and the Nature of Matter," in which he "proved" to his own satisfaction that only Boscovichean atoms were compatible with the observed conduction and nonconduction of electricity through material bodies. Again, it seems unlikely that Faraday convinced anyone, but this exercise did serve to stimulate him to return to his old preoccupation with the nature of electricity and magnetism. In 1846 he was led, in his "Thoughts on Ray Vibrations," to an embryonic form of the electromagnetic theory of light, later developed by James Clerk Maxwell. In both these essays Faraday was, as it were, conducting a dialogue with himself, attempting to clarify his own

ideas and to grasp the full implications of his own speculative hypotheses. These works therefore are of importance more because they reveal Faraday's mind to us than because they are important steps in the progress of electrical and magnetic science.

Last Researches: The Origins of Field Theory. The last, and in many ways the most brilliant, of Faraday's series of researches was stimulated by the quite specific comments of one of the few people who thought his theory of electricity worthy of serious attention. On 6 August 1845, William Thomson, the future Lord Kelvin, addressed a lengthy letter to Faraday, describing his success with the mathematical treatment of the concept of the line of force. At the end of the letter Thomson listed some experiments to test the results of his reasonings on Faraday's theory, and it was this that pushed Faraday once more into active scientific research. One of Thomson's suggestions was that Faraday test the effect of electrical action through a dielectric on plane-polarized light. As Thomson wrote:

> It is known that a very well defined action, analogous to that of a transparent crystal, is produced upon polarized light when transmitted through glass in any ordinary state of violent constraint. If the constraint, which may be elevated to be on the point of breaking the glass, be produced by electricity, it seems probable that a similar action might be observed.

The effect predicted by Thomson was one which Faraday had been seeking to detect since the 1820's, but with no success. Thomson's belief that it should exist reinforced Faraday's, and he returned to the laboratory to find it. As in the 1820's, his search was fruitless, but this time, instead of abandoning his search, he altered the question he put to nature. His own work in the 1830's had illustrated the convertibility of electrical and magnetic force. The failure to detect an effect of electrical force on polarized light might only reflect the fact that electrical force produced a very small effect which he could not detect. The force of an electromagnet was far stronger and might, therefore, be substituted in order to make the expected effect manifest.

On 13 September 1845 his efforts finally bore fruit. The plane of polarization of a ray of plane-polarized light was rotated when the ray was passed through a glass rhomboid of high refractive index in a strong magnetic field. The angle of rotation was directly proportional to the strength of the magnetic force and, for Faraday, this indicated the direct effect of magnetism upon light. "That which is magnetic in the forces of matter," he wrote, "has been affected, and in turn has affected that which is truly magnetic in the force of light." The fact that the magnetic force acted through the mediation of the glass suggested to Faraday that magnetic force could not be confined to iron, nickel, and cobalt but must be present in all matter. No body should be indifferent to a magnet, and this was confirmed by experiment. Not all bodies reacted in the same way to the magnetic force. Some, like iron, aligned themselves along the lines of magnetic force and were drawn into the more intense parts of the magnetic field. Others, like bismuth, set themselves across the lines of force and moved toward the less intense areas of magnetic force. The first group Faraday christened "paramagnetics"; the second, "diamagnetics."

The discovery of diamagnetism stimulated the production of theories to account for this new phenomenon. Ever since the work of Coulomb in the 1780's, most physicists had assumed (with Coulomb) the existence of polar molecules to account for magnetism. The simple thing to do, when faced with the apparent repulsion of diamagnetic substances by magnetic poles, was simply to assume some kind of "reverse" polarity leading to repulsion rather than attraction. Since such explanations necessarily involved the existence of magnetic or electrical "fluids," Faraday was skeptical. Furthermore, Faraday's attention was increasingly focused on the line of force, rather than on the particles of matter affected by the line of force. In his experiment on the rotation of the plane of polarization of a light ray, Faraday had noted that the "polarity" involved was in the line of magnetic force, not in the interposed glass. Experiments with diamagnetics further convinced him that there were no poles in diamagnetics but only reactions to the line of magnetic force.

He therefore rejected the polar theories of his contemporaries and substituted one of his own. Paramagnetics were substances that conducted the magnetic force well, thereby concentrating lines of force through them; diamagnetic substances were poor conductors of magnetism, thus diverging the lines of magnetic force passing through them. (See Figure 4.) A glance at the patterns of the lines of force was sufficient to disprove the polar theory: the lower figure is *not* the opposite of the top one. There are, in fact, no poles in diamagnetics. The top figure also indicates that there are no "poles" in paramagnetics either, if poles be defined as the termini of the magnetic force. As Faraday went on to show, the lines of magnetic force, unlike their electrostatic cousins, are continuous curves having no termini. They cannot be accounted for in terms of force-atoms under strain, and Faraday ignored his earlier model of interparticulate strain for the transmission of magnetic force.

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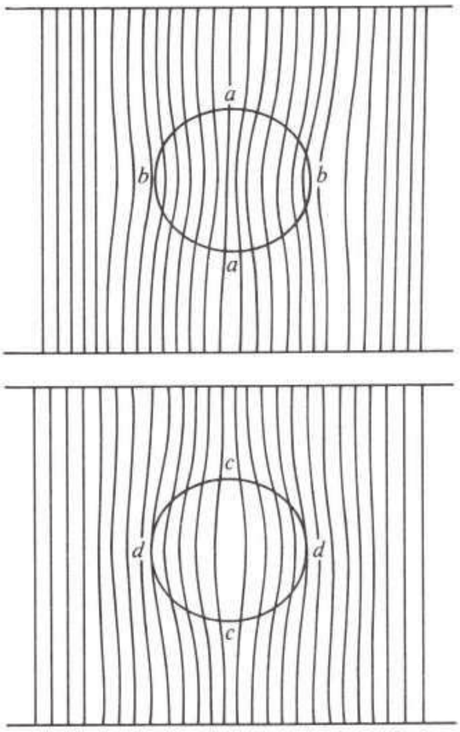

FIGURE 4. Diagrammatic representations of a paramagnetic substance (top) and a diamagnetic substance (bottom) in a uniform magnetic field. The "polarity" of the paramagnetic substance is represented by the compression of the lines of force at *aa*. There is no such compression in the diamagnetic substance; *cc* does not represent polarity opposite to that at *aa*.

Instead, he spoke of a "flood of power" marked out by the lines of force or compared a magnet to a galvanic circuit in which the magnet was the source of power; but the surrounding medium played the part of the connecting wires to transmit the magnetic "current." A magnet was described as the "habitation of lines of force."

Such explanations were manifestly unsatisfactory, for they provided no mechanism whatsoever for magnetic phenomena. They expressed metaphorically what Faraday felt the phenomena to be, but they gave little insight into their underlying causes. Only one point emerged clearly, and this point was of fundamental importance. Whatever the cause of magnetism, the manifestation of magnetic force took place in the medium surrounding the magnet. This manifestation was the magnetic field and the energy of the magnetic system was in the field, not in the magnet. By extension, the same could be said (and was so said by Faraday) of electrical and gravitational systems. This is the fundamental axiom of classic field theory.

By the mid-1850's Faraday had gone as far as he could go. He had provided a new perspective for those who would look on all manifestations of force in the phenomenal world. His description of this perspective was fuzzy and imprecise but capable of clarification and precision if taken up by someone who could share Faraday's vision. Such a man was James Clerk Maxwell, who, in the 1850's and 1860's, built field theory on the foundations Faraday had laid.

Faraday was unable to appreciate what his young disciple was doing. His mind deteriorated rapidly after the mid-1850's, and even if he had been able to understand Maxwell's mathematics, it is doubtful that he would have been able to follow Maxwell's chain of reasoning. As his mental faculties declined, Faraday gracefully retreated from the world. He resigned from all social clubs in the 1850's, concentrating what remained of his energies on his teaching functions at the Royal Institution. His Christmas lectures for a juvenile audience for 1859–1860, on the various forces of matter, and for 1860–1861, on the chemical history of a candle, were edited by William Crookes and have become classics. But even his lecturing abilities began to fade, and he was forced to abandon the lectern in 1861. In 1862 he resigned his position at the Royal Institution, retiring to a house provided for him by Queen Victoria at Hampton Court. On 25 August 1867 he died.

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(Moscow, 1951). John Tyndall, *Faraday as a Discoverer* (London, 1869, and many subsequent eds.) reveals what Faraday's orthodox friends thought of his physical heresies. Silvanus P. Thompson, *Michael Faraday. His Life and Work* (London, 1898) depicts Faraday as seen by a famous electrical engineer to whom Faraday's electrical discoveries far outweighed his work on field theory.

There are portraits of Faraday in the Royal Institution of Great Britain and the National Portrait Gallery.

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